Higher harmonic anisotropic flow measurements of charged particles at $\sqrt{s_{_{NN}}} = 2.76$ TeV with the ALICE detector *

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We report the measurements of elliptic flow v_2, as well as higher harmonics triangular flow v_3 and quadrangular flow v_4, in $\sqrt{s_{_{NN}}} = 2.76$ TeV Pb–Pb collisions, measured with the ALICE detector. We show that the measured elliptic and triangular flow can be understood from the initial spatial anisotropy and its event–by–event fluctuations. The resulting fluctuations of v_2 and v_3 are also discussed.

1. Introduction

Anisotropic flow is an good observable to study hot and dense matter created in heavy-ion collisions. The second order harmonic anisotropic flow v_2 [1], was studied from SPS to LHC energies [2–4] as summarized in [5]. Recently it has been argued that due to initial event–by–event geometry fluctuations the third harmonic v_3, called triangular flow, is finite [6]. In these proceedings, we will discuss the anisotropic flow and its fluctuations measured for charged particles in $\sqrt{s_{_{NN}}} = 2.76$ TeV Pb–Pb collisions.

2. Data sample and analysis

For this analysis in these proceedings the ALICE Inner Tracking System (ITS) and the Time Projection Chamber (TPC) were used to reconstruct charged particle tracks within $|\eta| < 0.8$ and $0.2 < p_{\rm t} < 5.0$ GeV/c. The VZERO counters and the Silicon Pixel Detector (SPD) were used for the trigger. Only the events whose primary vertex was found within 7 cm from the centre of the detector along the beam direction were selected. The tracks are required to have at least 70 reconstructed points in the TPC and a $\langle\chi^2\rangle$ per TPC cluster ≤ 4. The collision centrality determination utilized the VZERO detectors. From the study of the collision centrality determined

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by different detectors [7], *i.e.* ZDC, TPC, SPD and VZERO, the centrality resolution is found to be < 0.5 % rms for the most central collisions, while it increases to 2 % rms for peripheral collisions.

3. Results and discussion

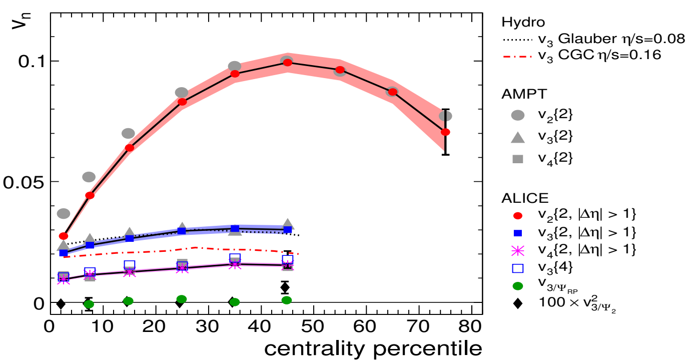

Fig. 1. v_2, v_3 and v_4 p_t–integrated flow as a function of centrality. Full and open blue squares show the $v_3\{2\}$ and $v_3\{4\}$, respectively. The full circle and full diamond are symbols for $v_{3/\Psi_{\rm RP}}$ and v^2_{3/Ψ_2}. In addition, the hydrodynamic calculations for v_3 and AMPT simulations are shown by dash lines and full gray markers. ALICE data points taken from [8].

Figure 1 shows the centrality dependence of v_2, v_3 and v_4 integrated over the interval $0.2 < p_{\rm t} < 5.0$ GeV/c. To suppress non–flow effects on the 2–particle cumulant analysis, a minimum $|\Delta\eta|$ gap of one unit was used between the correlated particles. We correct for the estimated remaining non–flow contributions by using HIJING [9]. We observe that the magnitude of v_3 is much smaller than v_2 (except for the most central collisions) and does not show a strong centrality dependence. These measurements are described by hydrodynamic calculations based on Glauber initial conditions and $\eta/s = 0.08$, while they are underestimated by hydrodynamic calculations with MC–KLN initial conditions and $\eta/s = 0.16$ [10]. The comparison suggests a small value of η/s for the produced matter. The v_3 measured from the 4–particle cumulant is about a factor 2 smaller than the 2–particle cumulant estimate, which can be understood if v_3 originates predominantly from event–by–event fluctuations of the initial spatial geometry [11]. At the same time, we evaluate the correlation between Ψ_3 and the reaction plane $\Psi_{\rm RP}$ via $v_{3/\Psi_{\rm RP}} = \langle\cos(3\phi - 3\Psi_{\rm RP})\rangle$. In addition the correlation of Ψ_3 and Ψ_2 also can be studied by a 5–particle correlator

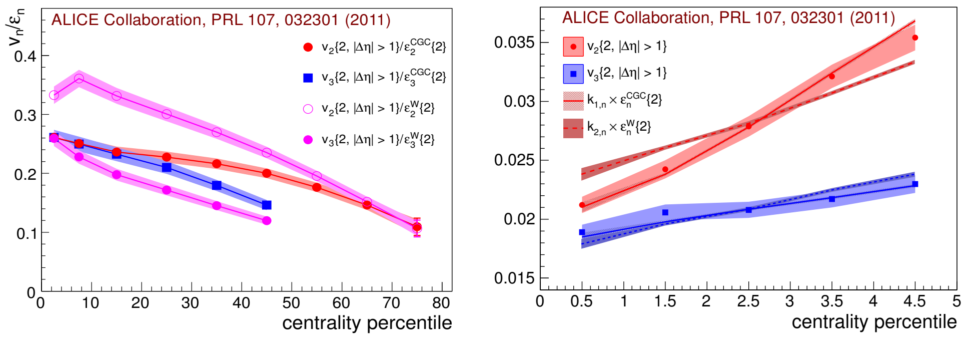

Fig. 2. (left) The centrality dependence of v_2/ε_2 and v_3/ε_3 for MC–Glauber and MC–KLN CGC initial conditions. (right) v_n and scaled ε_n as a function of centrality for the most central collisions (0–5%). The k_1 and k_2 have been used for eccentricities to match the 2% and 3% centrality percentile data. Figure taken from [8].

$v^2_{3/\Psi_2} = \langle\cos(3\phi_1 + 3\phi_2 - 2\phi_3 - 2\phi_4 - 2\phi_5)\rangle/v_2^3$. In Fig. 1 we observe that $v_{3/\Psi_{\mathrm{RP}}}$ and v^2_{3/Ψ_2} are consistent with zero within uncertainties. Based on these results, we conclude that v_3 develops as a correlation of all particles with respect to the third order participant plane Ψ_3, while there is no (or very weak) correlations between the Ψ_{RP} (also for Ψ_2) and the Ψ_3. Finally, from the comparison of AMPT model calculations with our measurements, we find that this model can describe the experimental data very well; there is only a slight overestimation of $v_2\{2\}$ in the most central collisions [12].

To investigate the role of viscosity on anisotropic flow measurements, we calculate the ratio v_2/ε_2 and v_3/ε_3. Here ε_2 and ε_3 are the eccentricity and triangularity of the initial spatial geometry which are defined by

$$\varepsilon_n = \frac{\sqrt{\langle r^2\sin(n\phi)\rangle^2 + \langle r^2\cos(n\phi)\rangle^2}}{\langle r^2\rangle}. \tag{1}$$

The definition of $\varepsilon_n\{2\}$ (also $\varepsilon_n\{4\}$) can be found in [13].

Figure 2 (left) shows the centrality dependence of the ratio v_n/ε_n. The ε_n are extracted from the MC–Glauber model (using the number of wounded nucleons) and the MC–KLN CGC model, denoted by $\varepsilon_n^{\mathrm{W}}\{2\}$ and $\varepsilon_n^{\mathrm{CGC}}\{2\}$, respectively. Based on the assumption that $v_n \propto \varepsilon_n$, we get $v_n\{2\} \propto \varepsilon_n\{2\}$ [13]. We observe that the $v_2\{2\}/\varepsilon_2^{\mathrm{W}}\{2\}$ is larger than $v_3\{2\}/\varepsilon_3^{\mathrm{W}}\{2\}$ in all centrality bins, which indicates significant viscous corrections. However, for the MC–KLN CGC model the magnitude of $v_2\{2\}/\varepsilon_2^{\mathrm{CGC}}\{2\}$ equals to $v_3\{2\}/\varepsilon_3^{\mathrm{CGC}}\{2\}$ in the most central collisions, which might be expected for an almost ideal fluid [10]. The ratio of $v_3\{2\}/\varepsilon_3^{\mathrm{CGC}}\{2\}$ decreases faster

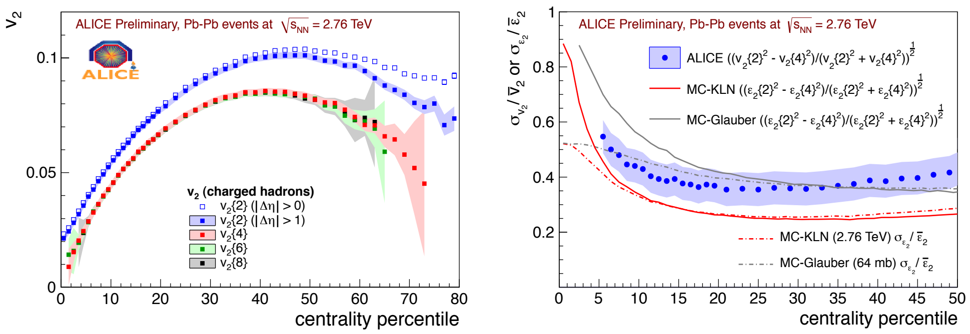

Fig. 3. (left) The centrality dependence of integrated v_2 in 1-2 % bins with different order cumulants. (right) Relative flow (eccentricity) fluctuations versus centrality.

than $v_2\{2\}/\varepsilon_2^{\rm CGC}\{2\}$ from central to peripheral collisions, which is consistent with larger viscous corrections to v_3. The collective flow should be directly sensitive to the change of the initial spatial geometry since the viscous effects do not change too much in the small centrality range. In Fig. 2 (right) we observe that in this centrality range v_3 does not show a strong centrality dependence while the $v_2\{2\}$ increases significantly. The comparison of the scaled initial eccentricity shows that $v_2\{2\}$ and $v_3\{2\}$ can only be simultaneously described by $\varepsilon_2\{2\}$ and $\varepsilon_3\{2\}$ from the MC–KLN model.

In order to reduce the event–by–event fluctuations within a centrality bin, we plot the integrated v_2 as a function of centrality in narrow bins, 1% centrality bins for 0–20% and 2% bins for 20–80% [7]. Elliptic flow estimated from 2–particle azimuthal correlations, $v_2\{2\}$, was obtained by using two different pseudorapidity gaps ($|\Delta\eta|>0$ and $|\Delta\eta|>1$). The difference between the two measurements can be understood as resulting from non–flow effects. At the same time, the results of 4–, 6– and 8–particle cumulants estimates are shown in Fig. 3 (left). The good agreement of the multi-particle cumulants indicates that with 4–particle cumulants non–flow is strongly suppressed, so that there is little gain in suppressing it further by higher order cumulants (like 6– and 8–particle).

As shown by Gaussian fluctuations studies [14], in the limit of small fluctuations ($\sigma_v < \bar{v}$), we can estimate the participant plane flow and its fluctuations with:

$$\bar{v}_n \approx \sqrt{\frac{v_n^2\{2\} + v_n^2\{4\}}{2}} \text{ and } \sigma_{v_2} \approx \sqrt{\frac{v_2^2\{2\} - v_2^2\{4\}}{2}}. \tag{2}$$

However, in the case of only fluctuations [14], we have

$$\bar{v}_n = \frac{\sqrt{\pi}}{2} v_n\{2\} \text{ (or } \sigma_{v_n}/\bar{v}_n = \sqrt{4/\pi - 1}\text{) and } v_n\{4\} = 0. \tag{3}$$

Also based on the assumption that v_n is proportional to ε_n, the centrality dependence of eccentricity and its fluctuations should show behavior similar to that of flow. In Fig. 4 (left) we indeed observe a similar centrality dependence of ε_2 with v_2 and the following equations are valid

$$\varepsilon_2^2\{2\} \approx \varepsilon_2^2 + \sigma_{\varepsilon_2}^2,\ \varepsilon_2^2\{4\} \approx \varepsilon_2^2 - \sigma_{\varepsilon_2}^2 \tag{4}$$

with the exception of the most central collisions (for which $\sigma_v < \bar{v}$ does not hold).

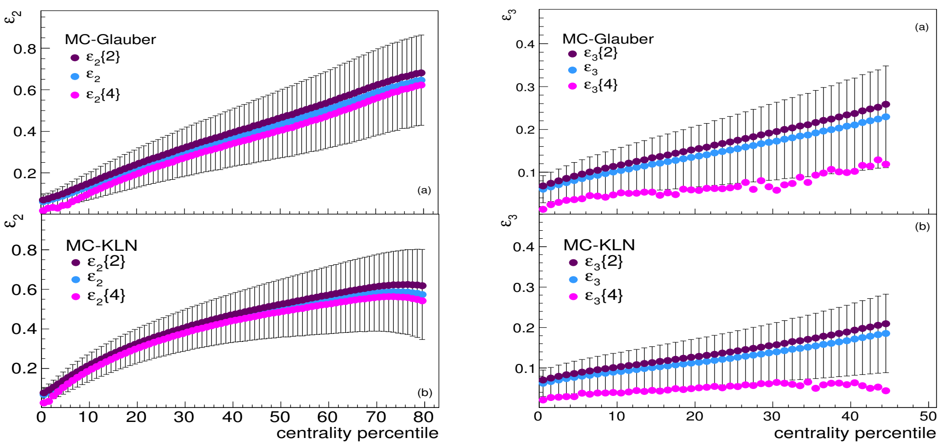

Fig. 4. Centrality dependence of eccentricity (left) and triangularity (right) from MC–Glauber model and MC–KLN model. The error bar is the fluctuations of the eccentricity (triangularity). The ε_n is extracted from the Eqs. (1), the definitions of $\varepsilon_n\{2\}$ and $\varepsilon_n\{4\}$ can be found in [13].

The centrality dependence of the relative flow fluctuations $\sigma_{v_2}/\bar{v}_2$ are plotted in Fig. 3 (right). We find that the magnitude of relative flow fluctuations is around 40%. Also we show the comparison of the relative flow fluctuations to $\sigma_{\varepsilon_2}/\varepsilon_2$ (extracted from Eqs. (4)) from both the MC–Glauber model and the MC–KLN model. In mid-central and mid-peripheral collisions, the MC–Glauber model can describe the flow fluctuations while the MC–KLN model underestimates the measurements. In the more central collisions, neither the MC–Glauber nor the MC–KLN can describe the data. At the same time, we notice that $\sigma_{\varepsilon_2}/\varepsilon_2$ from both the MC–Glauber model and the MC–KLN model reach $\sqrt{4/\pi - 1}$ in the most central collisions, which is consistent with the predictions if there are only fluctuations [14].

Assuming that v_3 originates from the initial geometry fluctuations (there are only flow fluctuations), we expect that $v_n\{2\} = \frac{2}{\sqrt{\pi}}\bar{v}_n$ and $v_n\{4\} = 0$. However, as we have shown in Fig. 1, the $v_3\{4\}$ has a finite magnitude.

In order to understand the fluctuations of v_3, we look at the centrality dependence of triangularity ε_3. In Fig. 4 we observe that $\varepsilon_3\{2\} = \frac{2}{\sqrt{\pi}}\varepsilon_3$ is still valid (or the ratio $\sigma_{\varepsilon_3}/\varepsilon_3$ equals to $\sqrt{4/\pi - 1}$), but it seems that $\varepsilon_3\{4\} \approx \varepsilon_3 - \sigma_{\varepsilon_3}$ in the centrality bins we present here. Whether the fluctuations of ε_3 are the dominant contribution to the fluctuations of v_3 is currently unknown.

4. Summary

In these proceedings we have presented the results on anisotropic flow measured in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$=2.76 TeV by ALICE at the LHC. The measurements of higher harmonic anisotropic flow, in particular v_3, provide new constraints on the initial anisotropy as well as the shear viscosity to entropy density ratio η/s.

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